SESSION III

Chairman: **Professor D. C. Colley**

INVITED TALK

GEC's Wartime Contribution

Mr W. E. Willshaw

Introduction

I am glad of the opportunity to talk about the contribution of the GEC Research Laboratories to the research on and development of the cavity magnetron.

The laboratories at Wembley were opened in 1923 following the company's decision, during the First World War, to found laboratories covering fundamental problems arising in the manufacture of electrical products and to pursue research on new products. Experience in wartime had shown how dependent this country had been on research carried out abroad. This was the first research laboratory in this country specifically for the electrical manufacturing industry, with control independent of product manufacture.

The laboratories were built on a green field site in north Wembley, with ready rail access to London for scientific meetings. Its founder was C. C. Paterson, who had strong views on the facilities and organization needed. He came from the NPL, where he was in charge of the Electrotechnics Department and Photometry, and was Director at Wembley until his death in 1948.

Early work on magnetrons

In 1937 I joined Eric Megaw at Wembley where he had worked since 1930 on valves for the shortest possible wavelengths. He was convinced that the magnetron diode offered the best opportunity for this. He was very familiar with work in progress in Europe, especially in Czechoslovakia, Germany, France, Holland, in the USSR, and in Japan and the USA.

In the period since 1924, three distinct modes of operation were recognized for the magnetron diode and its split-anode versions. These were the electronic mode with frequency dependent on magnetic field only, the dynatron mode with negative resistance both at low and higher frequencies, and the travelling-wave mode, which is our concern today. There was considerable confusion in interpreting operation, arising especially from the overlap of the latter two modes. But in 1934 Posthumus in Holland developed a successful four-segment magnetron and published his travelling-wave theory. This was followed by Megaw and Herriger and Hulster with ideas on precessional resonance between electron orbits and a standing wave of potential round the anode, establishing a basic procedure for design. It was used for several years before the War.

In this, no special reason was seen for the cathode diameter to be limited to a small fraction of the anode diameter, but almost all valves used tungsten filament cathodes which were quite adequate for early CW needs. Indeed early German data on the use of large tungsten spiral cathodes indicated a fall in efficiency and this misleading result was widely believed.

Early use for communication

In 1937 a four-segment glass-envelope valve (E880, NT75) was designed at Wembley, and used at 40-60 cm in a study for the Admiralty. This had an anode diameter of 7 mm, a thoriated tungsten cathode of 0.25 mm, giving an output around 10 W at 50 cm wavelength. The objects of the study were to confirm that a magnetron self-oscillator could be used in an engineered system and that the communication range would be limited by the horizon, so that ships' receivers could not intercept beyond this range.

A complete system was designed and made at Wembley for shipboard use, with magnetron transmitter, frequency stabilized by a resonator, stabilized power supplies, square-wave modulator

and super-regenerative receiver using an acorn signal oscillator. After initial-local trials, twelve sets of equipment were built at the GEC Telephone Works at Coventry and installed in a variety of ships including a capital ship and a flotilla of destroyers. They were used in wartime and after one year's experience judged to be most successful in operation. It was concluded that a magnetron could be used in an operational system, providing adequate care was taken in the provision of stable power supplies and frequency stabilization. Figure 1 shows the transmitter with magnetron and all its stabilizing equipment.

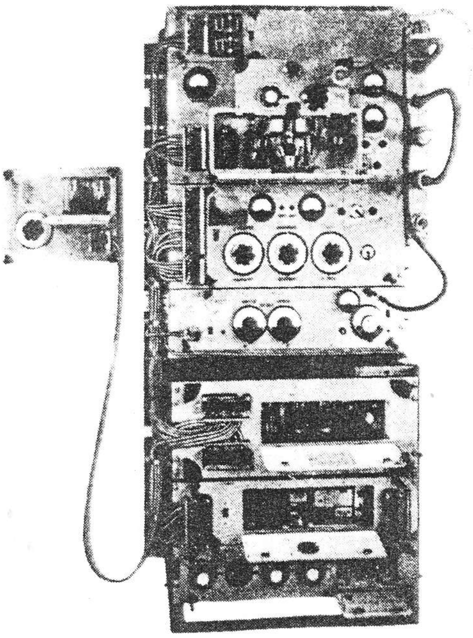


Fig. 1
Complete transmitter, with output attenuator, keying load absorber and frequency meter

Work on multi-segment magnetrons

In 1938, Gutton and Berline of SFR in Paris reported the performance of their recent multi-segment valves. The anode was formed of a self-resonant interdigital system of between six and eighteen segments and the cathode a tungsten filament. Efficiencies between 10 and 15% were obtained over the range 10-20 cm. These results were discussed with Megaw during a visit to Paris in 1939 when it was arranged that samples would be sent to him. The outbreak of war delayed this.

A few weeks later contact was made with Randall and Boot at Birmingham who had demonstrated their six-segment copper-block valve, operating on the pump, giving a power of 150 W CW at 9.9 cm wavelength with 7 kV, 0.15 A input. The magnetic field of 1300-1400 Oe was produced by a large electromagnet of 13 cm air gap. A 0.75 mm tungsten filament was used in a 12 mm diameter anode, 40 mm long. Figure 2 shows a section of the anode block. Figure 3 shows this tube, which was water cooled.

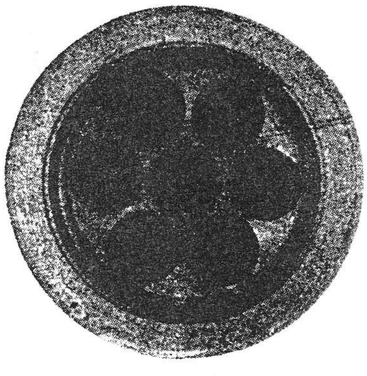


Fig. 2
One of the first six anode blocks made

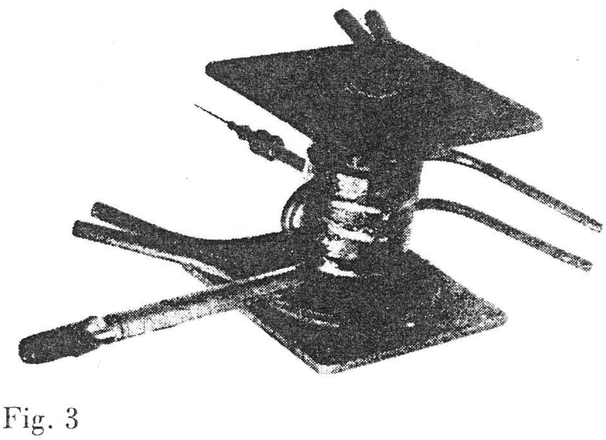


Fig. 3
The first (demountable) cavity magnetron

In discussing the design, Megaw suggested that it could be simplified, and the magnet weight greatly reduced, by using metal ends to close the block and side-arm supports for the cathode. In collaboration with Randall and Boot he produced a sealed-off valve with these changes, fitting a 7 cm magnet gap. Its performance was similar to that of the Birmingham valve and reached 500 watts CW, limited by emission from the tungsten- filament cathode.

In this design the gold-seal technique, originated in Wembley a few years before, was used as a clean and simple method of attaching the copper end discs to the block, after mounting the cathode on side arms. Figure 4 shows this completed valve, called the E1188 No.1.

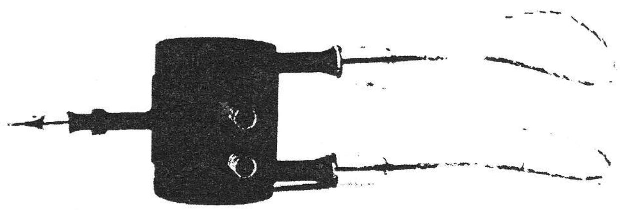


Fig. 4
E1188, No. 1. Improved model of Randall-Boot tungsten-filament magnetron; designed and made in collaboration with Birmingham University (Design completed 16th May, 1940).
CW or pulse output of the order of 0.5 kW at 10 cm. Electromagnet, weight 50 lb

Following increasing demand for a 10 cm valve for airborne use, it was then decided to make a design more suited for this. It had a large-diameter thoriated-tungsten spiral cathode, and a shorter anode length so that an existing small permanent magnet could be used. Air cooling replaced the water cooling of the earlier valve.

In May 1940, two samples of Gutton's 16 cm valve arrived. They had twelve segments, 10 mm anode diameter and had been fitted with 4 mm diameter oxide-coated cathodes. They had already given a pulse power of 1 kW. An emergency pulse modulator was built giving 200-2000 μs pulses at 50 p.p.s. and measurements made over a range of magnetic field and current. In particular it was found that oscillations could be maintained with a primary emission less than 1% of the anode current, confirming the importance of secondary emission with the oxide-coated cathode, as discovered at Wembley in 1933.

In addition, two ranges of operation were observed with a wavelength difference of 2%. These were interpreted as corresponding to twelve-segment and six-segment oscillation of the anode system.

In view of these results, two models of the new compact design of 10 cm copper-anode valve were fitted with thoriated-tungsten and oxide-coated cathodes of diameter 3 mm and 4.5 mm respectively in a 10 mm diameter anode. Outputs around 1 kW pulse were obtained on 25th June with the lower-field permanent magnet of 1100 Oe and 10 kW with 1400 Oe from the electromagnet. The wavelength was near 9.8 cm for both valves. In view of all these results, the use of the oxide-coated cathode was regarded as established.

Final design of the first copper-block magnetron

The new design was basically satisfactory, except that the magnetic field for maximum efficiency was too high for the existing permanent magnet. Accordingly the design was recalculated for eight cavities instead of six, keeping the wavelength at 10 cm. The modified design, now E1189, was standardized for naval use (NT 98). Figure 5 shows this and Figure 6 shows a section of the construction. E1198 (CV38), a variant for 9.1 cm operation, was used in the first airborne equipment.

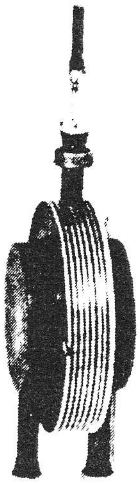


Fig. 5
Magnetron type E1189, the original design for operation in aircraft

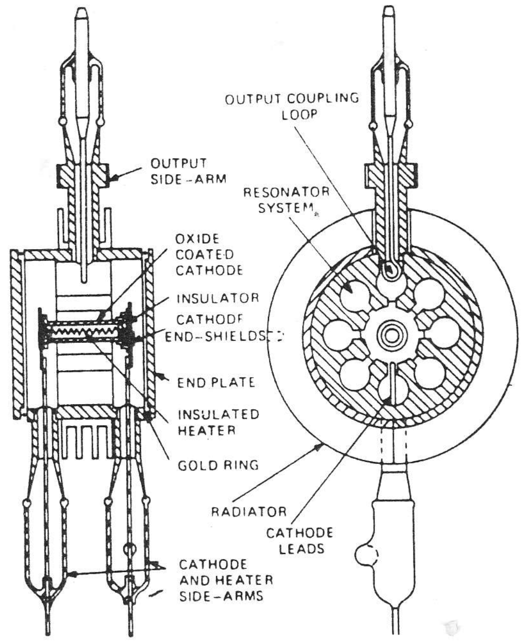


Fig. 6
Magnetron type NT98

The first sample of the E1189 was taken to the USA by the Tizard Mission in August 1940.

By now the basic requirements for production for both naval and aircraft use had been solved, though there were still problems in stable operation.

The work at Wembley was greatly extended by the setting up of pre-production teams of scientists and assistants. As a contribution to the national effort the Patent Department had been closed down at the start of the War and provided staff of both types, as did other Departments. The Research Laboratories of the BTH at Rugby, which had been associated with the earlier Birmingham work on high-power klystrons, had also started work on magnetrons and a close relationship was formed with GEC, with regular meetings on current problems. The later work described here, particularly on 3 cm valves, benefited greatly from this collaboration.

By the end of 1941, when newer types began to appear, about 2000 valves of the NT98 type had been produced.

Mode change and strapping

With larger numbers of valves in use in equipment, defects in operation became apparent, especially those due to mode change. These resulted from the use of several cavities to increase anode and cathode size and therefore power.

With N cavities, the mode of oscillation with π phase change between adjacent cavities resulted in $N/2$ repeats of RF field round the anode, with N even. This mode number could vary from $N/2$ down to one with small frequency change and any one of these modes might be excited.

In 1941, Sayers at Birmingham investigated this and evolved a relatively simple method of separating the frequencies of the modes. This involved connecting together, by short lengths of wire, those cavities required to be in phase, and was remarkably effective at least for wavelengths around 10 cm. Figure 7 shows the separation achieved in a typical eight-cavity valve.

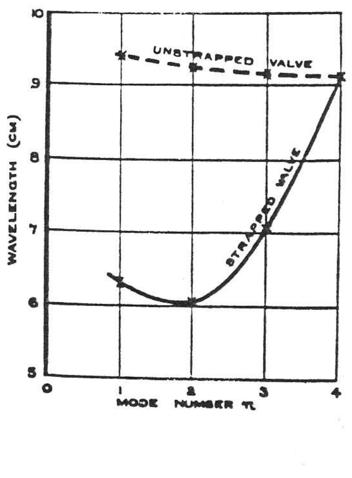


Fig. 7
Mode spectrum of unstrapped and strapped valves

Separation of frequency was not the only requirement for stable operation, as discussed later, but a big increase in efficiency followed. The 10 cm E1198, which was not strapped, operated at 7.5 kW output with 10% efficiency. The strapped version CV56 operated at 90 kW output with 40% efficiency.

The preferred π mode was now excited at much lower voltage than the other modes, though these could still be excited by Fourier components at lower voltages.

This improvement by strapping meant that large increases of power could be obtained, without change in anode design, provided that improvements were made to the heat dissipation of the cathode, amounting to 3-6% of the mean anode power, as a result of cathode bombardment.

The resulting CV76 operated at 500 kW output with 50% efficiency, the coupling to the output waveguide being by direct RF radiation from the output probe. It was used extensively in naval and ground radar. Similar designs were produced for 9.1 and 8.5 cm with the same power and efficiency.

Contact with theoretical groups

During the work at Wembley, close collaboration was developed with Professor Hartree's theoretical group in Manchester. One result of the Manchester work was an expression for the threshold anode voltage which must be exceeded if electrons are to reach the anode in the presence of cavity oscillations. Good agreement was obtained with experimental values, as indicated in Figure 8, as well as with those arrived at by earlier simple calculations. This figure shows threshold voltage as a function of magnetic field for different modes of an eight-cavity valve.

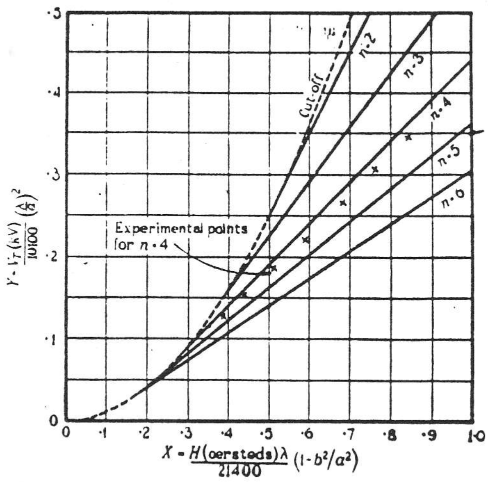
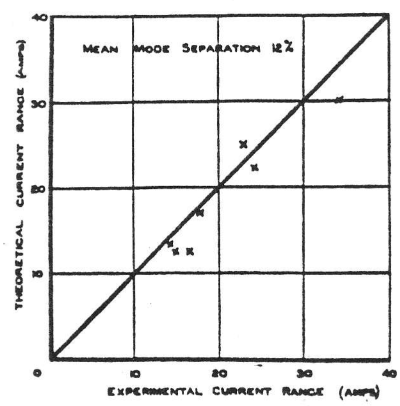


Fig. 8
Relation of threshold voltage to magnetic field-strength for various values of n

These values of threshold voltage led to the identification of modes observed after mode change, and the realization that higher-order Fourier components could be excited at voltages close to that of the π mode.



Understanding of the mode-change problem was, however, aided by the concept of the instability voltage. This is the voltage necessary for small signals to be generated to initiate the oscillations necessary for the threshold voltage to be effective. In practical valves these are not very different and their relative values are dependent on the ratio between anode and cathode diameters. Thus conditions may be found to allow operation in the required mode over the required current range. Figure 9 shows the relation between theoretical and experimental current range for

Fig. 9 *Relation between theoretical and observed current-range for 3 cm magnetron*

different cathode sizes in a later 3 cm magnetron. This theory was of considerable value in designing new valves and in modifying the performance of existing ones.

One result of the calculation of electron orbits in the presence of space charge was the realization that at the high magnetic fields necessary for good efficiency, electrons arrive at the anode surface with a tangential velocity close to that of the rotating wave with which they are interacting. Those returning to the cathode do so with small energy since their penetration into the anode field is small. This results in a simple expression for maximum efficiency, which is in reasonable agreement with experience for high magnetic fields.

Figure 10 shows theoretical and experimental values for a typical eight-segment valve, allowance being made for the RF power lost in bombardment of the cathode. This shows the very high efficiencies which may be obtained.

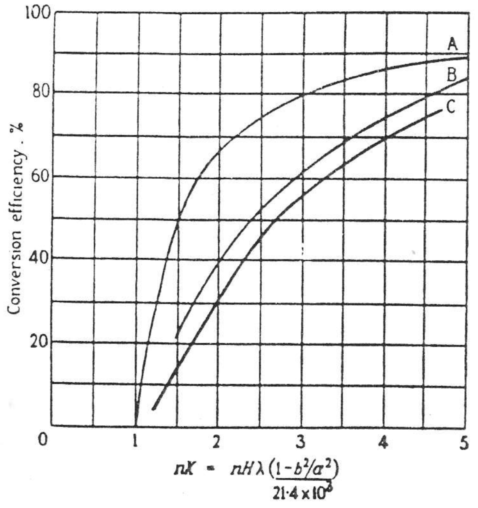


Fig. 10
Theoretical and measured efficiencies,
A, Theoretical efficiency; B, Measured efficiency for a typical 8-segment valve; C, Mean (measured) curve for a large number of designs

Higher-power valve for 10 cm

Towards the end of 1942 there was a demand for a 10 cm valve of 4-5 times the 500 kW then available. The development took a long time due to continuous mode-change problems. Many trials were made with large anode and cathodes, heavy strapping for large mode separation but without success in reaching the current required. Eventually the significant factors already mentioned, controlling mode change, were sufficiently understood to enable the required power to be reached and Figure 11 shows the valve produced. This had 10 segments operated at 40 kV, 100 A with 2000 Oe field and gave at least 2 MW. It was air cooled, with a waveguide output system coupling to a 3" x 1" waveguide, through a taper system.

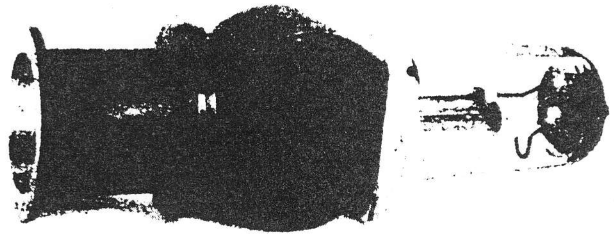


Fig. 11
High-powered air-cooled 10 cm magnetron

Valves for 3 cm

In 1941 there was a need for operation around 3 cm. At this time little of the work on stable operation of 10 cm valves had been done, especially on the use of strapping, but it was known to be necessary to increase considerably the number of cavities or to reduce anode and cathode sizes. Early valves were made with anode sizes similar to those of the 10 cm valves, and with up to 22 cavities with cathode areas only slightly less. The efficiencies were between a quarter and a half of

the best 10 cm valves and there were always troublesome mode changes. When the success of strapping had been established, many forms were tried without success.

It was thought that the lower relative accuracy of forming the cavities for 3 cm might be the cause of poor performance, and attention was turned to increasing cavity size. A construction was devised in which the ends of the cavities were closed, as shown in Figure 12. The cavity wavelength was then close to twice the cavity length. Equalizing the wavelengths of individual cavities arose through the machining operation of turning to length. In an early trial, end plates were fitted to a 10 cm unstrapped valve, resulting in oscillation around 3 cm with output of 80 kW at 12% efficiency. In spite of a large number of trials, the scheme was rejected since performance was no less variable than with open-ended designs.

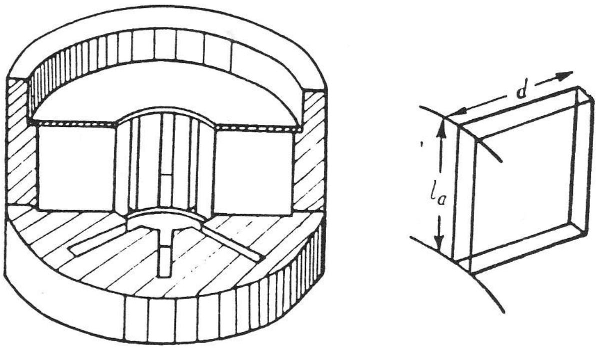


Fig. 12
Closed-end structure

The first developed 3 cm valve, called the CV108, had 18 cavities and was unstrapped. The cavity number was reduced to 12 and ring straps added. Now called the CV208, it generated 30 kW at 20% efficiency and was a complete replacement for the earlier CV108. Experimental valves were produced in August 1943, with pre-production samples in November.

In a modification, part of the load waveguide was added to the valve, output coupling being adjusted in manufacture by a piston closing one end of the output waveguide. A glass cover protected the cathode support. This was called the CV214.

With later needs for higher power, a new design called the CV355 was produced. It generated 200 kW output, with 100 W mean, and had an efficiency of 40%. It had 14 cavities with double ring strapping and operated at 22 kV, 23 A with a magnetic field of 5500 Oe in the valve anode. The cathode was of the oxide-coated type, with metal loading to minimize voltage flashing and was mounted on heavy tungsten supports to minimize vibration. In this design, problems of voltage flashing, mode change, cooling of the cathode and design of output circuit were particularly important.

Thus, since the demonstration of the first practicable 10 cm valve in August 1940, with a few kilowatts pulse output, power of a few hundred kilowatts had been obtained at 3 cm, three years later.

Impact of American techniques and experience

Of course the receipt of the first multi-cavity design in the USA caused a rapid build-up of R and D work and the results were fed back in the shape of advances in materials and constructional techniques, new designs and theoretical work.

Typical were the use of end-supported cathodes and packaged magnets, and the later use of the 'rising sun' anode to avoid the need for straps. Figure 13 shows a selection of later low-power 3 cm valves making use of these features. Figure 14 shows a cross section of the AX9 rising-sun valve. With 18 cavities it gave a pulse power of nearly 1 MW which was achieved at 3.1 cm with 240 W mean power. The power was taken from the back of one of the cavities by a slot into a vacuum-enclosed output waveguide.

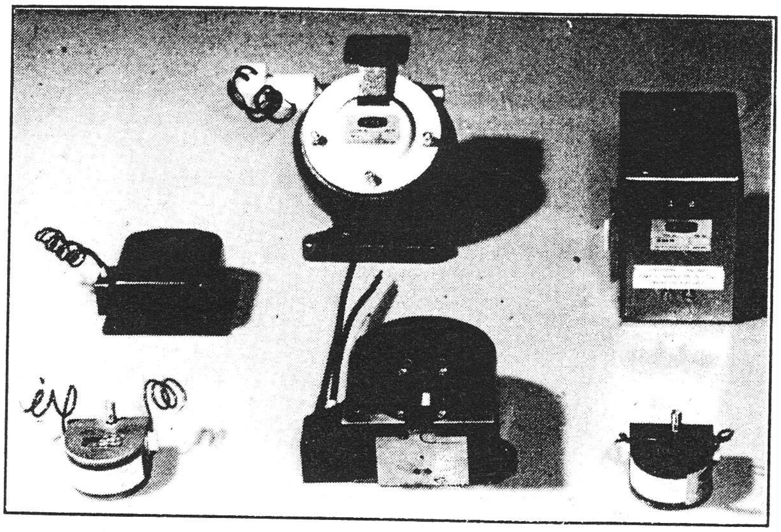


Fig. 13
A selection of low-power 3 cm valves

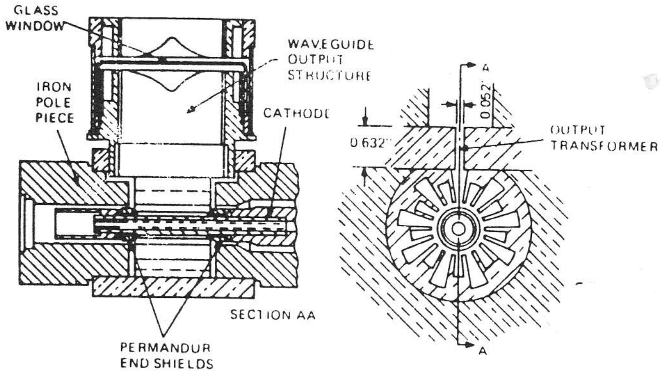


Fig. 14
Cross sections of AX9 magnetron

Conclusion

This review summarizes briefly the GEC's contribution to the progress of the magnetron up to the end of the wartime years, latterly in close collaboration with BTH. Although it concentrates chiefly on designs for radar, there was significant work on CW designs in which relatively wide tuning was achieved mechanically, with similar mean power and efficiency to pulsed valves. This work also led to increased understanding of the magnetron behaviour at very low current.

After the War, work continued on millimetre waves as well as on higher-power centimetre waves.

Reference
Willshaw, W. E., "Microwave Magnetrons: a brief history of research and development". *G.E.C. Journal of Research* 3, No. 2, 1985, p. 84.

DISCUSSION

Professor Colley:

Would anyone like to make a comment on the industrial contributions, or ask a question about them?

Dr Jelley:

You showed a three-centimetre one with end-plates actually sealing. Were the lengths of the slots half a wavelength or something? Why didn't that short it out completely? (Not one that had strapping but one that was actually sealed with flat plates.)

Mr Willshaw:

Well, one looked upon this as a waveguide and so the axial length of the slot was not very significant at all - nothing like as significant as it would be without the end-plates on.

Dr Jelley:

I am surprised that it doesn't short out the RF, because it is unlike the strapping.

Mr Willshaw:

No, the main problem was - of course, we decided this later - that the coupling between adjacent elements was of course much smaller than it was in the hole-and-slot devices. It was only due to a leakage into the cathode space that one got coupling, whereas in the earlier hole-and-slot device one had magnetic field linking into the end-space.

Dr Lawson:

It is not an important point, but I seem to remember hearing somewhere that the Japanese had done some important early work on magnetrons. Of course, we have only relatively recently known about it - is that right?

Mr Willshaw:

Yes, they did quite a lot of work. Okabe was the man who did the work which was published in the United States. It was done in Tokyo, before the War.

Dr Lawson:

What kind of magnetrons were these, then?

Mr Willshaw:

I never really saw any details about that so I do not really know.

Professor Colley:

Most people do by the look of it! [laughter]

Mr Tomlin:

It was rather a surprise at the IEE 1985 Symposium, when the Japanese gave a paper, to see for the first time some photographs, and some actual models and frankly some of them were almost identical with ours. The cavities were the same form, the numbers of cavities were more or less the same. There was one version which was, shall we say, an artist's version, in that all the surplus metal had been cut away between the cavities in order to make a very nice pattern, but had no value at all. But we were very surprised to find that some of these had actually been used as early as 1937 in one of the battleships. So they had in fact got cavity magnetrons long before we had, and you find the article, which is the actual talk that they gave, in the Radar Symposium book 1939-45 issued by the IEE. I cannot give you actual titles I am afraid.*

Mr Burman:

There is also a paper that describes those magnetrons by Nakajima from Japan Radio Company**. I have a copy of it here, but I did not think that it would be appropriate to bring it up today, actually. [laughter]

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*Nakajima, S., "A history of Japanese radar development to 1945" in Russell Burns (Editor), *Radar development to 1945*, Peter Peregrinus (on behalf of the IEE), London, 1988, 243-258. P.M.R.

Nakajima, S., *The study of the microwave magnetron*, Japan Radio Company, April 1947. Mr Burman has also given details concerning a paper on Russian work: Alekseev, N. F. and Malairov, D. D., "Generation of high-power oscillations with a magnetron in the centimeter band," *J. Tech. Phys.* (Russian), **10, April 1940, 1297-1300: received by the IRE(US), May 22nd 1943 and, as translated by Bensen, I. B., published in *Proc.IRE*, 1944, March. P.M.R.

Actually the question I wanted to ask Mr Willshaw relates to the production of the first eight-cavity magnetron as opposed to the six-cavity version. Your description and your explanation of it that it was required to improve the efficiency within the available magnet, ties up with Megaw's paper presented in 1946. If you read Dr Bowen's *Radar Days*, he has a rather more story-telling type of version. He describes how he turned up at the Bell Telephone Laboratories with the magnetron and they X-rayed it and found that the one that he had had eight cavities and when he rang up Megaw to find out what had happened, he was told "Oh, my goodness, yes, I asked the foreman to make ten anode blocks with six cavities, and one with seven and one with eight and the one with seven was the one that didn't work."

Is that really the case, or it that just a bit of historical nonsense?

Mr Willshaw:

Yes, I think that is just another bit of historical mis-management. There is no point in going to odd numbers of cavities in view of Megaw's earlier experience, although, undoubtedly, the seven-cavity one would have worked quite well but with all the mode-change problems of it, presumably.

Professor Colley:

Thank you, Mr Willshaw. I am afraid that we will have to terminate that discussion.

I will now call on Dr Bryant, from the University of Michigan, whose talk will concentrate on British, American and Canadian collaboration during the War.